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INDOOR AIR QUALITY IN A MULTIFAMILY APARTMENT BUILDING BEFORE AND AFTER ENERGY RENOVATION

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ABSTRACT
Buildings are responsible for a substantial portion of global energy consumption. Most of the multifamily residential buildings in central Europe built in the 20th century do not satisfy the current requirements on energy efficiency. Nationwide remedial measures are taken to improve the energy efficiency of these buildings and reduce their energy consumption. Since the impact of these measures on the indoor air quality is rarely considered, they often compromise indoor air quality due to decreased ventilation and infiltration rate. We compared the indoor air quality in a multifamily apartment building in Slovakia before and after energy renovation, during two subsequent winters. Measurements of temperature, relative humidity, concentrations of CO_2, formaldehyde, NO_2, and volatile organic compounds were performed during one week in January 2015 in 20 apartments in one multifamily building in Slovakia. Subjective evaluation of the indoor environment and occupant satisfaction using questionnaire has been also performed. The measurements were repeated in January 2016, after the building was energy-renovated. The renovation included thermal insulation of the façade. Natural ventilation was used in the building. Exhaust ventilation was present in bathrooms and toilets. No changes to the ventilation were done during renovation. After renovation, the ventilation rates in the apartments were significantly lower than before. Concentrations of formaldehyde, TVOC and certain individual VOCs were higher. The occupants indicated more dissatisfaction and a higher prevalence of some sick building syndrome symptoms after renovation. When residential buildings in central Europe are upgraded to more energy efficient ones, the retrofitting effort should include improved ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ. Without these considerations, energy reconstruction can adversely affect the quality of the indoor environment.

Keywords: Residential building; Energy retrofitting; Formaldehyde; VOC; Air change rate

1. INTRODUCTION

The building sector is responsible for one third of global energy consumption. The need to reduce energy consumption and greenhouse gas emissions became a national priority across the European Union member countries (BPIE, 2011; Meijer et al., 2009). A large proportion of the European population resides in multi-family buildings. Therefore, the residential sector represents a major potential target group for national programs supporting energy efficiency improvements of existing buildings and climate change mitigation. Multi-family residential buildings in Slovakia well represent the residential building stock of Eastern and Central Europe. Most of these buildings were built from 1948 to 1990. About 70% of these buildings do not fulfil the current European requirements for energy efficiency. Building retrofit campaigns for existing multi-family buildings have been implemented (EU, 2010). However, the effect of these programs on indoor air quality and occupant well-being is often neglected. Consequently, the countries fail to capitalize on the opportunity to improve indoor environmental quality on a nationwide scale.

Adding insulation to the building envelope or replacing inefficient single glaze windows with more efficient ones may lead to tighter buildings, resulting in reduced intake of outdoor air (infiltration rate). This may increase the concentration of indoor-generated air pollutants (Øie et al., 1998). Occupant exposure occurring in the residential environment can be substantial. These exposures may be associated with numerous long-term and acute health effects (Seppänen and Fisk. 2004). Therefore, there is a need to assess the impact of the currently applied building renovation practices, with the primary focus on energy conservation, on the residential indoor environmental quality, and provide recommendations for policy makers, engineers and the public. The objective of this study was to compare the indoor air quality in a multifamily apartment building before and after energy renovation, during two subsequent winters.

2. METHODS

The study was performed in a nine floor residential dwelling with forty apartments located in the building. Twenty apartments were selected across the residential building, equally distributed on the lower, middle and highest floors of the building. A questionnaire survey and measurements were carried out during two winter seasons, in January 2015 when the building was still in its original condition, and in January 2016 after energy saving measures have been implemented. The same apartments were investigated in both winter seasons during a period of eight days. The renovation of the dwelling included envelope and roof insulation, replacement of old windows for energy efficient ones and hydraulic balancing of the heating systems. Natural ventilation was used in the building. Exhaust ventilation was present in bathrooms and toilets. No changes to the ventilation were done during renovation.

Temperature, relative humidity and CO_2 concentration were measured in bedrooms of the apartments using HOBO U12-012 data loggers and Vaisala CARBOCAP CO_2 monitors. All devices were calibrated before the measurement campaign began. The data were recorded in 5 minutes intervals for eight days in each apartment. A set of passive samplers for NO_2, formaldehyde and VOC were placed centrally in living rooms of each investigated apartment. The samplers were always positioned at least 1.5 m above floor level. Sampling of NO_2 was carried out using IVL´s (Swedish Environmental Research Institute) diffusive samplers (Ferm, 2001). The gas molecules diffused into the sampler where they were quantitatively collected, which gave a concentration value integrated over time. NO_2 was analyzed by wet chemical techniques using a spectrophotometric method. The limit of detection for NO_2 was 0.5 μg/m^3 for the sampling period of one week. Formaldehyde was sampled using DSD-DNPH UmeX-100 (SKC Inc., Eighty Four, PA, USA). The limit of detection was 0.03 μg/m^3 for formaldehyde. High performance liquid chromatography analyses of the samplers were carried out. Perkin-Elmer adsorption tubes filled with 200 mg Tenax TA, were used for passive sampling of VOC. They were thermally desorbed at 275 °C for 7 minutes and calibrated by application of microliter amounts of solution of toluene in diethyl ether on Tenax tubes, before their shipping to Slovakia. The tubes were wrapped in aluminium folia and stored at room temperature until the measurement started. Gas chromatography/mass spectrometry analysis of the tubes was carried out in the laboratory. The limit of detection for the individual VOC was 0.2 µg/m^3. All parameters were also measured outdoors, on one of the balconies located on the third floor of the building.

Air exchange rates (AER) were calculated in the occupants' bedrooms from the occupant generated CO_2 concentrations for each night. CO_2 concentrations between 20:30 and 6:30 were used together with the occupants' body weight, height and room volume. A questionnaire regarding the occupants' comfort and wellbeing was administered to one occupant in each apartment during the measurement week, both before and after renovation. Stata statistical package release 12.1 (StataCorp LP, College Station, Texas, USA) was used for data analyses. Pearson's correlation coefficient was used to look for correlations between variables. Paired t-test and Wilcoxon signed rank test, where applicable based on normality of distribution, were used to compare the obtained results from the investigated apartments before and after renovation.

3. RESULTS

The overall average air temperature was significantly higher in the dwellings after renovation (22.2 °C) than before (20.9 °C), ($p<0.01$). The average temperatures in 25% of the apartments before renovation did not fulfil the criterion of the optional range (20-24 °C). Under-heating occurred in these particular apartments, where the mean temperature ranged between 18.3 °C and 19.7 °C. After renovation all 20 apartments met the required range of the thermal comfort criteria. The mean relative humidity was slightly lower before renovation (46%) than after renovation (48%), but the difference was not statistically significant ($p>0.1$).

The difference in CO_2 concentration between the pre-retrofit and post-retrofit condition was statistically significant. The median of the average night-time concentrations was 1300 ppm before renovation and 1870 ppm after renovation. During night-time, increase of CO_2 concentration was observed in each of the investigated apartments. The ratios of the CO_2 concentrations after and before renovation were between 1.03 and 3.6 (average ratio after-to-before was 1.49). The frequency distribution of the average CO_2 concentrations is shown in Figure 1.

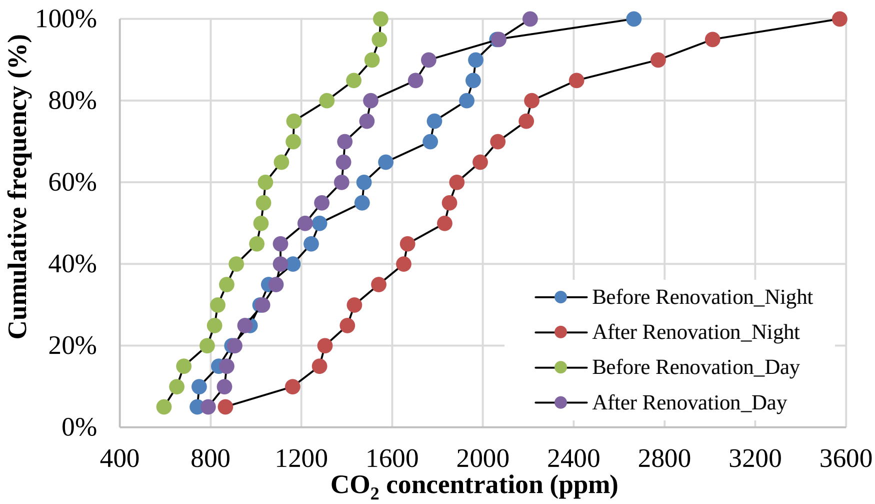

Figure 1. Cumulative frequency distribution of the average CO_2 concentration in the bedrooms during the day and night before and after renovation of the residential building.

The AER showed significant difference between the values obtained before and after renovation. Before renovation the average AERs was 0.61 h^{-1}. After renovation (0.44 h^{-1}) it dropped below the recommended minimum (0.5 h^{-1}) (Figure 2).

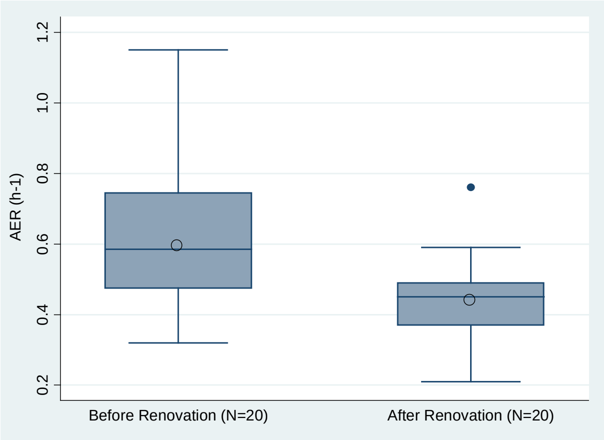

Figure 2. Boxplots of the AER before and after renovation of the residential building

The AER was lower than 0.5 h^{-1} in 40% of the apartments before renovation (ranged from 0.32 to 0.49 h^{-1}). The rest of the apartments met the criterion (ranged from 0.54 to 1.15 h^{-1}). After renovation, 85% of the apartments had a lower AER than 0.5 h^{-1}.

The NO_2 concentration was characterized by log-normal distribution. According to the WHO Guidelines for Indoor Air Quality the recommended annual average value for NO_2 concentration indoors is 40 µg/m³ (WHO, 2010). This limit was exceeded during the measurement week only in one apartment, where the NO_2 was 42.1 µg/m³ before renovation. Lower average NO_2 concentration was observed in the apartments before renovation (Figure 3). However, the difference between the two conditions was not statistically significant. In half of the apartments an increase of NO_2 after renovation was observed. The ratios between the indoor and outdoor concentration showed that in several apartments the indoor NO_2 was higher than the outdoor concentration indicating the presence of indoor sources.

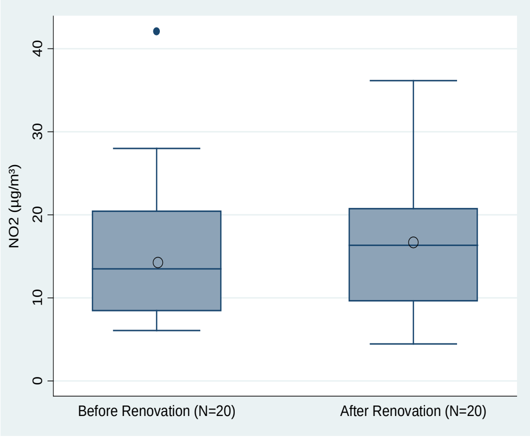

Figure 3. Boxplots of the NO_2 concentrations before and after the renovation of the residential building

Figure 4 shows boxplot of the formaldehyde concentrations before and after renovation of the building. The difference between the two conditions was statistically significant. The World Health Organization recommends a 30-minute average formaldehyde concentration of 100 µg/m³ (WHO, 2010). Although the concentrations of formaldehyde were below this limit in all apartments, an increase in the formaldehyde concentration was observed in 75% of the apartments after renovation. Among these apartments, the ratio of formaldehyde concentrations after and before renovation was between 1.09 and 2.5 (average 1.62). In the rest of the apartments only slight decrease was observed (average ratio 0.89).

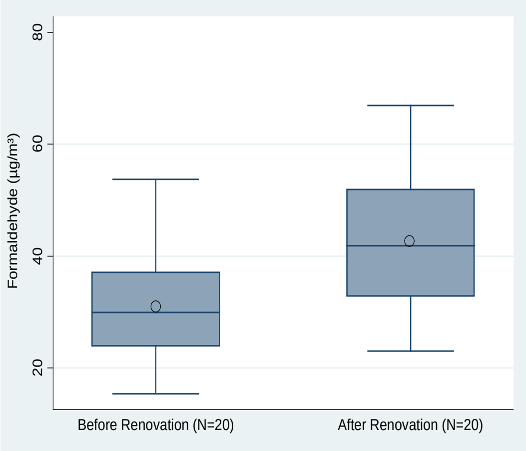

Figure 4. Boxplots of the formaldehyde concentrations before and after the renovation of the residential building.

Individual VOCs were also identified. The concentration of heptane, limonene, haxanal and isobutanol was significantly higher after renovation than before. The concentration of benzene and hexanoic acid was significantly higher before than after renovation. The difference in TVOC concentration was not significant, although the overall mean TVOC across all apartments was higher after renovation (772 µg/m³) than before (569 µg/m³) (Figure 5). Over 80% of apartments had a weekly average TVOC concentration above the limit of 300 µg/m³ recommended by Seifert (1990). A substantial increase was seen in seven apartments after renovation, with ratios from 1.4 to 8.4.

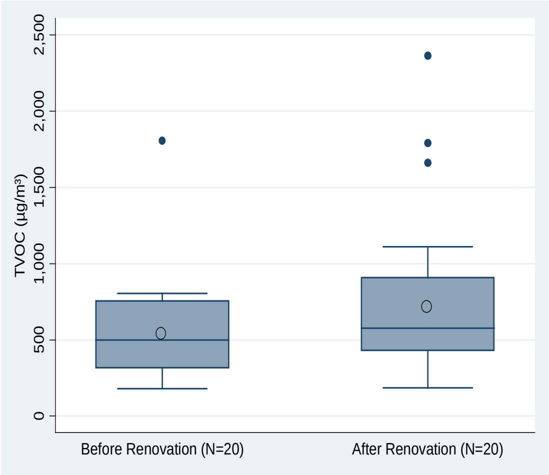

Figure 5. Boxplots of TVOC concentrations before and after the renovation of the residential building.

Most of the occupants did not indicate any problems with the indoor air quality before renovation, while after renovation their satisfaction decreased. Higher acceptability of the perceived air quality was observed before renovation. The prevalence of selected sick building syndrome (SBS) symptoms among occupants (those filling the questionnaire) is shown in Figure 6.

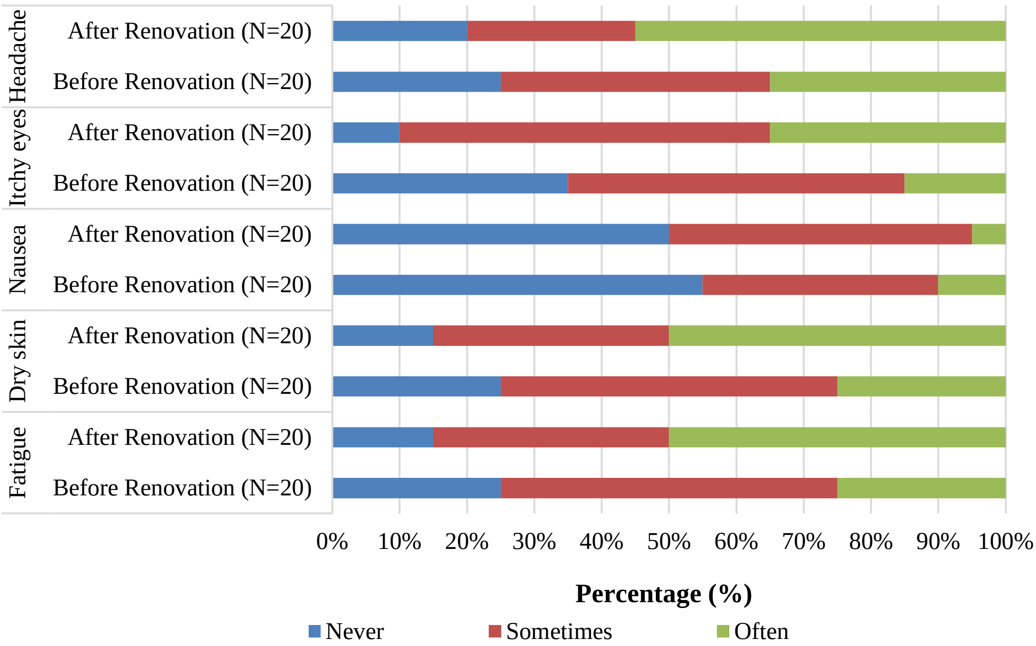

Figure 6. Prevalence of sick building syndrome symptoms before and after renovation.

Significant positive and relatively strong correlation was found between formaldehyde and CO_2 concentration, and relative humidity, negative correlation with AER (Table 1). Significant positive correlation was observed between AER and acceptability of air quality (r=0.79) and negative correlation between formaldehyde concentrations and acceptability (r=-0.53).

Table 1. Correlation coefficients between the measured parameters and concentrations of pollutants.

	NO_2	Formald.	TVOC	CO_2	T	RH
NO_2						
Formald.	-0.09					
TVOC	-0.09	0.27				
CO_2	0.2	**0.57***	0.16			
T	-0.12	0.14	0.09	0.06		
RH	-0.05	**0.48***	**0.3***	**0.57***	**0.56***	
AER	-0.19	**-0.59***	-0.21	**-0.87***	-0.16	**-0.51***

*$p<0.05$

4. DISCUSSION

Indoor air in residencies is a dominant contributor to personal exposure, because people spend a substantial fraction of the day at home. The results of this study further support the fact that energy renovation without considering the indoor environment can lead to deterioration of indoor air quality.

There was no clear pattern in the change of NO_2 concentrations, nor in the change of indoor/outdoor ratios from before renovation to after renovation. The ratios indicated the presence of indoor combustion sources in some of the apartments. However, none of the apartments in the present study had gas stoves and other combustion devices. Candle burning is however common during the winter seasons, especially during Christmas holiday period (Langer et al., 2015). Measurements of longer duration and detailed identification of the sources of NO_2 would validate the current results.

An earlier review of formaldehyde in indoor environment reported that insulation material could be one of the major sources of formaldehyde (Salthammer et al., 1995). Foam board materials, which were also used for envelope insulation in the current study, may cause high emissions. Moreover, fitting of the residential building with this insulation resulted in a tighter building construction and decreased ventilation in the apartments after renovation. The significant negative correlation between AER and formaldehyde concentration reflects that decreased ventilation may have contributed to increased formaldehyde concentrations. Furthermore, significant positive correlation was found between relative humidity and formaldehyde, which is in line with expectations (Parthasarathy et al., 2011).

The TVOC concentrations exceeded 300 $\mu g/m^3$ in a large fraction of the apartments already before renovation. More than 100% increase of TVOC was observed in three apartments. In these apartments furniture replacement (carpet/sofa) was reported after the first round of measurements. These activities could have caused an increase in TVOC levels. This is in agreement with similar observations in studies where new materials, furniture, paints may have led to increased TVOC concentrations (Park and Ikeda, 2006).

The occupants indicated to be more satisfied with the IAQ before renovation. Positive correlation was found between AERs and acceptability of the indoor air quality and negative correlation was observed between formaldehyde concentrations and acceptability of IAQ. Similar results were reported by Maddalena et al. (2015); lower perceived air quality was observed when the concentration of pollutants increased, which was the case at lower ventilation rates. Wolkoff (2013) reported that with specific focus on poorly perceived IAQ, hexanal (linseed oil in building materials and human debris, e.g. skin oils), hexanoic acid (an oxidative degradation product from linseed oil, skin oils and cooking) and limonene (a common fragrance used in numerous consumer products) may be some of the most important compounds. These three individual VOCs were among the most abundant ones in our study. Higher concentration of hexanal and limonene was observed after renovation, while the concentration hexanoic acid was higher while the building was in its original state.

We found higher prevalence of SBS symptoms after renovation of the apartment building. Both concentrations of pollutants and occupants' perception and well-being may be affected by decreased AERs. However, multivariate regression models did not produce significant p-values for the associations between SBS symptoms and AER. No significant associations were observed between SBS symptoms and the concentrations of the measured indoor air pollutants. However, chemical substances emitted from building materials, including formaldehyde and other organic compounds may be associated with SBS symptoms (Salthammer et al., 2010). The lack of such association in our study may be partly due to the low number of investigated apartments. Further studies on the relationship between SBS symptoms and AER in larger number of dwellings before and after renovation are warranted.

Numerous studies have reported decreased prevalence of SBS symptoms and improvement of occupant health after moving into green buildings, where lower levels of several key pollutants, such as particles, NO_2, VOCs and allergens were measured (Colton et al., 2014; 2015). These studies could provide some lessons to be learned regarding the potential to improve indoor air quality, when energy retrofitting of existing buildings is performed.

5. CONCLUSION

The current study indicates that energy renovation of apartment buildings by simply adding thermal insulation may tighten the building, leading to reduced ventilation rates and poorer indoor air quality. Significantly higher CO_2 concentrations and lower AERs were observed in the building after its renovation. Lower AERs resulted in increased levels of formaldehyde. The TVOC concentrations exceeded 300 μg/m³ in a large fraction of the apartments before renovation, but even higher concentrations were measured after renovation. The occupants indicated to be more satisfied with the indoor air quality before renovation. Higher satisfaction with IAQ was indicated at higher AERs and lower formaldehyde concentrations. Building renovation also resulted in higher prevalence of some of the sick building syndrome symptoms, such as itchy eyes, headache and fatigue. When old, leaky residential buildings in central Europe are upgraded to more airtight and energy efficient ones, the retrofitting effort should include improved ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ. Energy reconstruction without considering its impact on the indoor environment can adversely affect the quality of the indoor environment in the apartments.

6. ACKNOWLEDGMENTS

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